Neutrinos as Probes and/or Candidates of Dark Matter

INFO 07
Santa Fe Summer Workshop on
Implications of Neutrino Flavor Oscillations
July 2 - July 6, 2007

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arXiv:0707.0196 [astro-ph] H. Yüksel, S. Horiuchi, J. Beacom, S. Ando
arXiv:0706.4084 [astro-ph] H. Yüksel, J. Beacom, C.Watson
arXiv:astro-ph/0605424 C.Watson J. Beacom, H. Yüksel, T. Walker
arXiv:astro-ph/0512411 J. Beacom, H. Yüksel

Dark Matter Proposed Long Ago

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

Nebulae as Gravitational Lenses

F. ZWICKY

ON THE CLUSTERING OF NEBULAE

BY F. ZWICKY

NUCLEAR GOBLINS AND COSMIC GAMMA RAY BURSTS

F. ZWICKY†

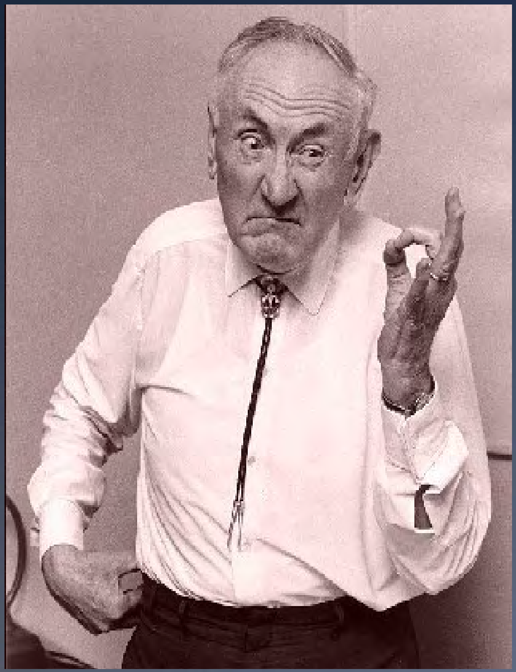
COSMIC RAYS FROM SUPER-NOVAE

BY W. BAADE AND F. ZWICKY

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

Communicated March 19, 1934

1930s: Zwicky proposed DM to explain the mass to light ratio Coma galaxy cluster

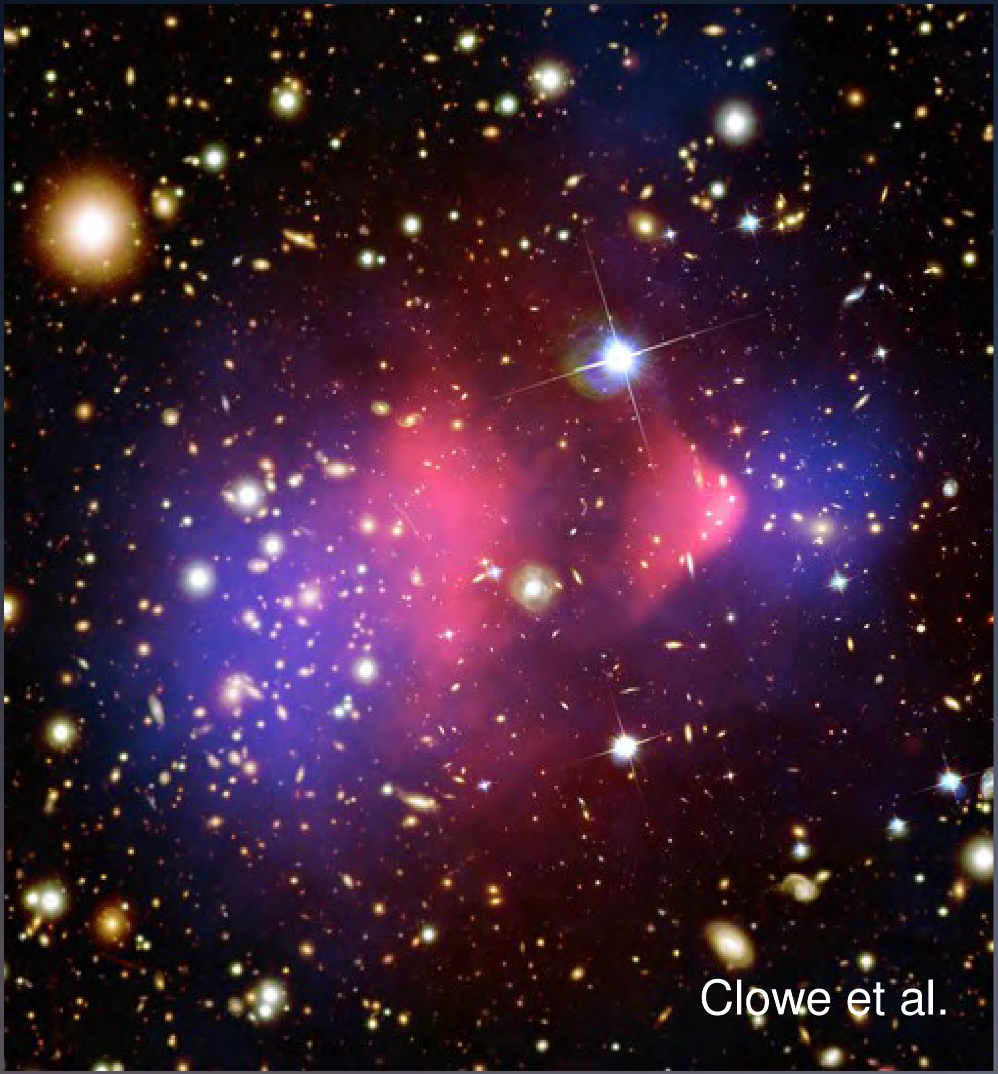


1975: Rubin announced most stars in spiral galaxies orbit at roughly the same speed

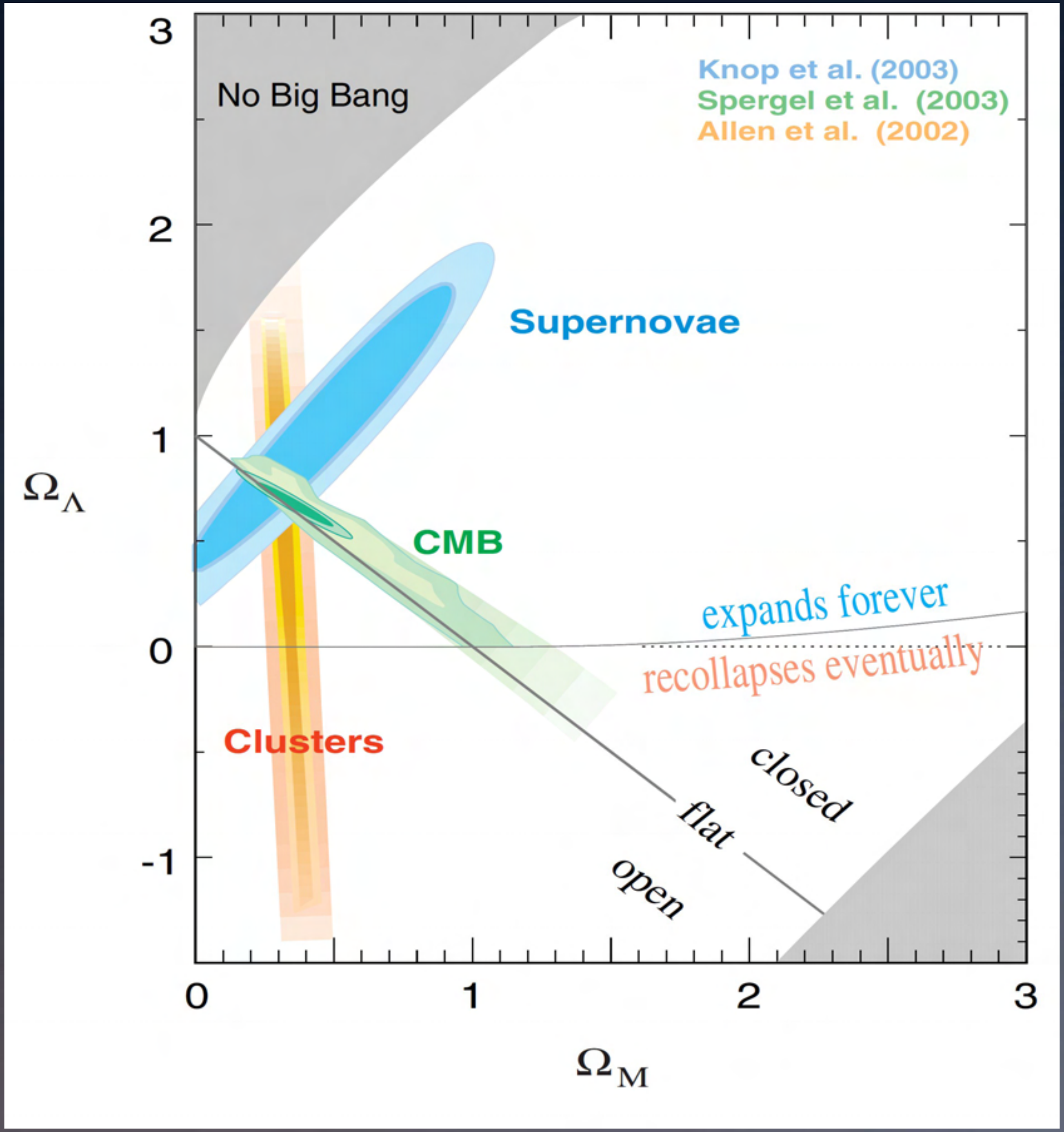
Where Is It?

Gravitational lensing probes the distribution on cluster scales

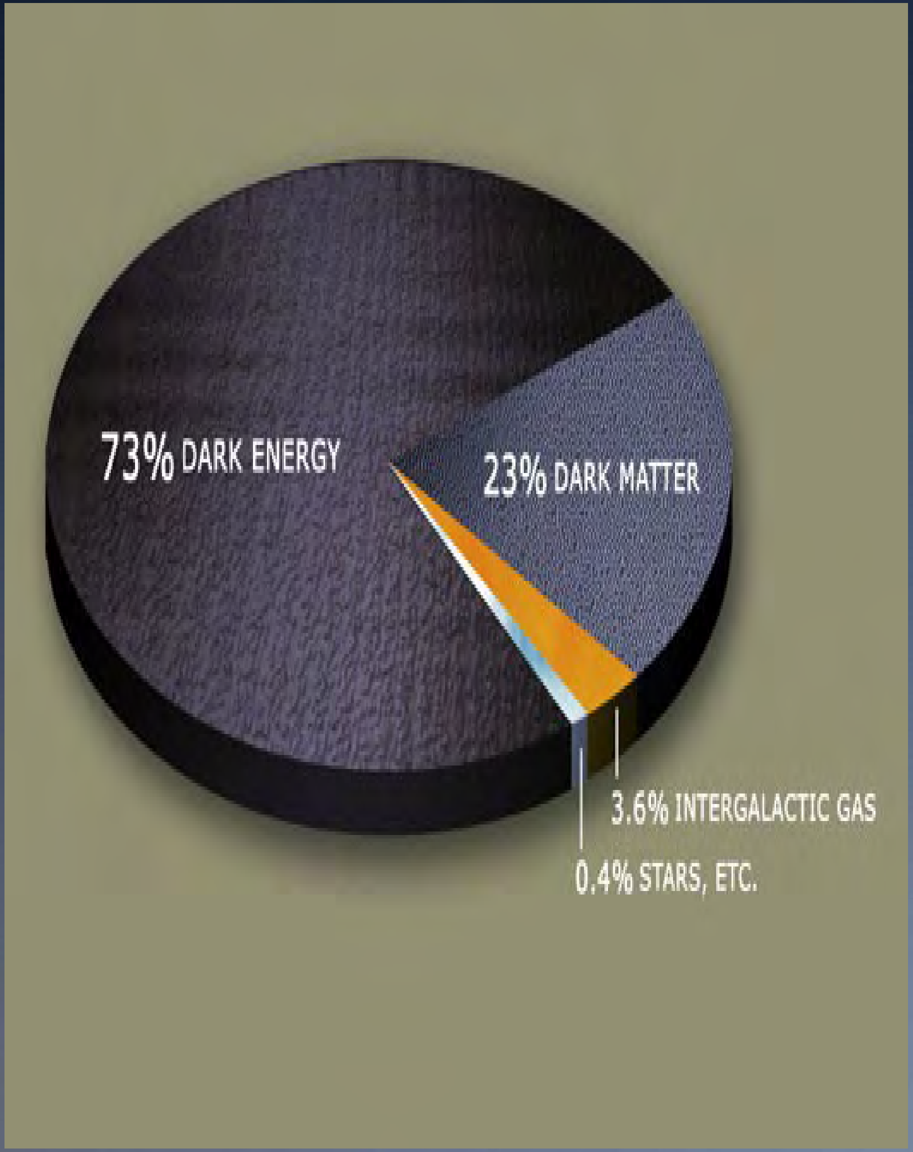
Blue: dark matter (weak lensing) Purple: gas (x-ray emission)



How Much?



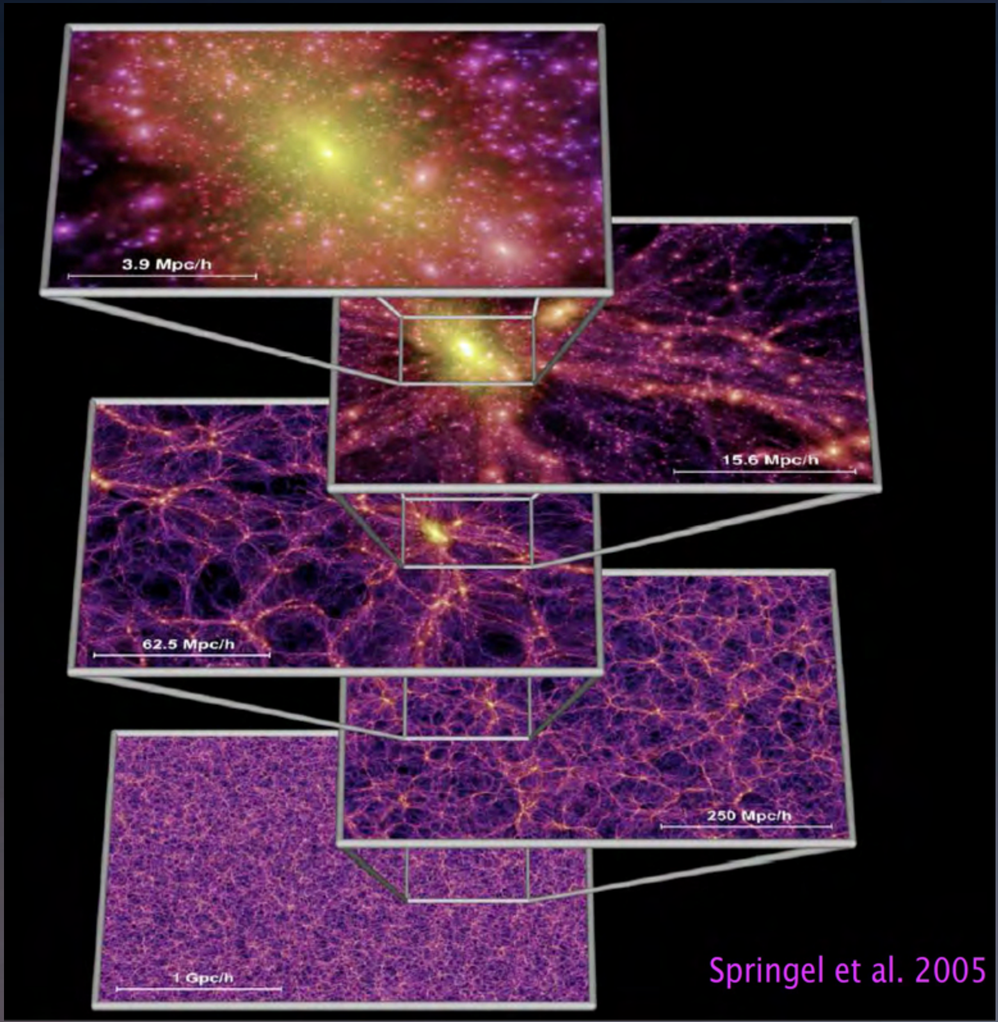
3
2
1
0
-1
Ω_Λ
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
expands forever
recollapses eventually
Clusters
closed
flat
open
0
1
2
3
Ω_M



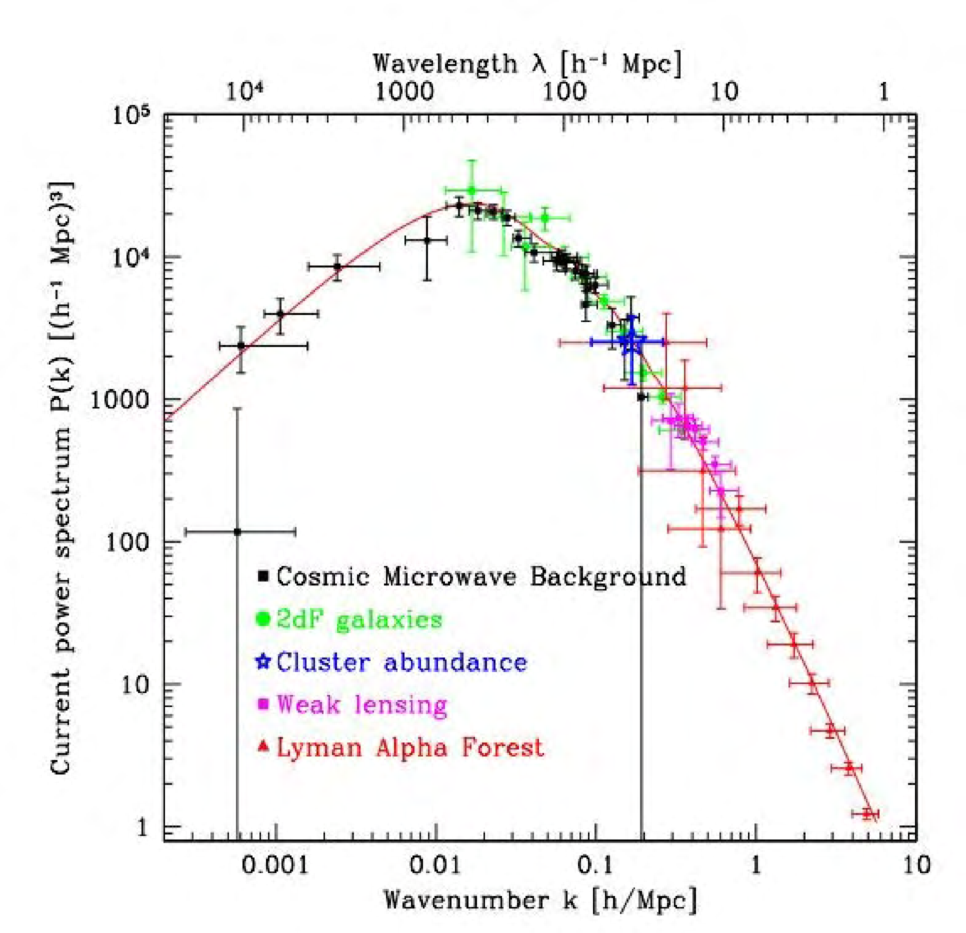
73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

How is DM distributed in the Universe?

Primordial Fluctuations → Gravitational Collapse → Structure Forms from Smallest to Largest Scales

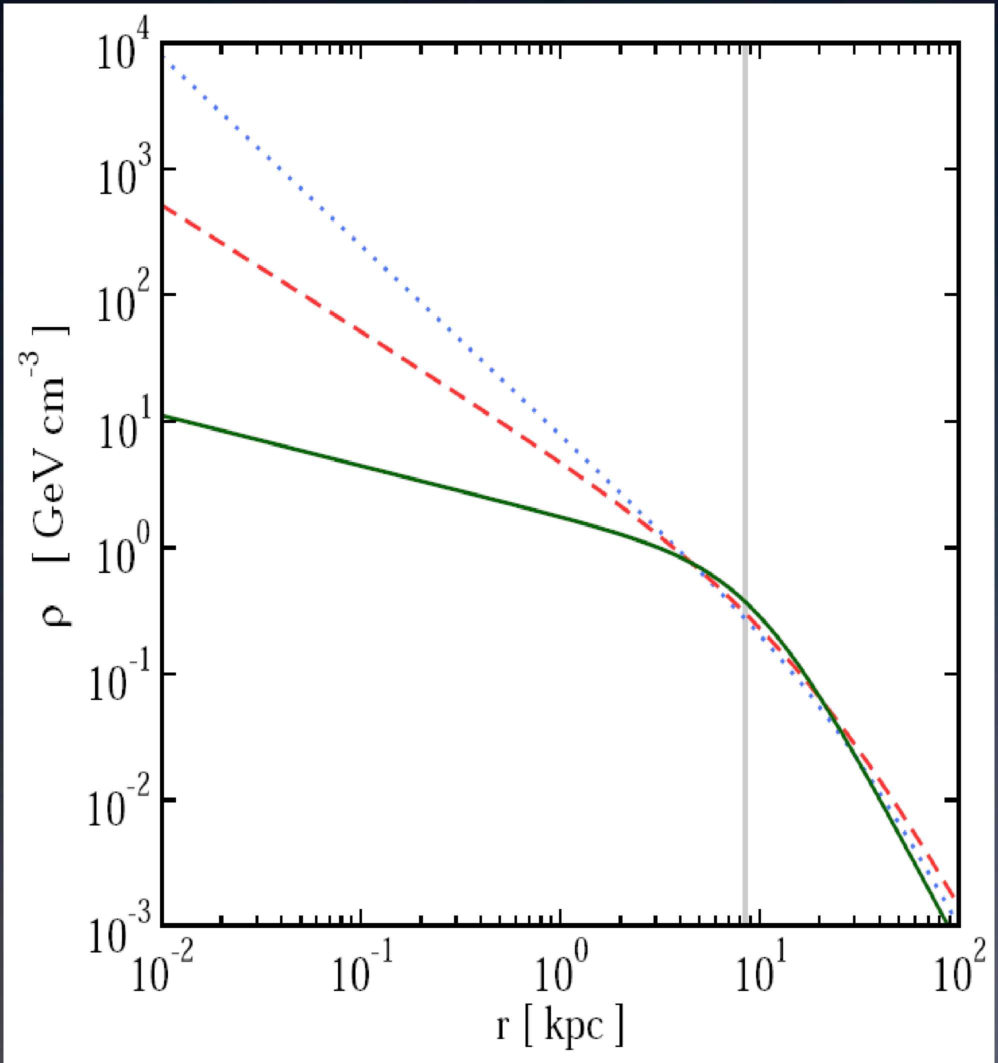


Springel et al. 2005



Tegmark

DM Distribution in Halos



$$\rho(r) = \frac{\rho_0}{(r/r_s)^\gamma[1+(r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

	α	β	γ	r_s	$\rho(R_{sc})$
Moore	1.5	3	1.5	28	0.27
NFW	1	3	1	20	0.3
Kravtsov	2	3	0.4	10	0.37

But What Is It?

Axions, SUSY Particles, UED LKP, Fuzzy DM,
Massive Black Holes, Light DM, Sterile Neutrino,
Super Heavy X Particle, MACHOs, ...
or name your own favorite!

All These Candidates Need to be Tested

What is the role of neutrinos in this Search?

(I) LIMITS ON STERILE NEUTRINO WARM DARK MATTER FROM THEIR RADIATIVE DECAYS

Sterile Neutrinos are very Capable

- Generate universal lepton asymmetry
  - Abazajian, Bell Fuller, Wong 2005; Asaka Kusenko Shaposnikov 2006; Kishimoto Fuller Smith 2006
- Facilitate reionization
  - Hansen Haiman 2004, Biermann Kusenko 2006; O'Shea Norman 2006; Mapelli Ferrara Pierpaoli 2006
- Mediate active neutrino oscillations
  - Hidaka Fuller 2006; Smirnov Zuchanovich-Funchal 2006; Gelmini Palomares-Ruiz Pascoli 2004
- Explain pulsar kicks
  - Kusenko Segre 1999; Fuller Kusenko Mocioiu Pascoli 2003; Barkovich D'Olivio, Montemayor 2004
- Explain lsnd anomaly (maybe not necessary anymore)
- Help r-process nucleosynthesis
  - Fetter, McLaughlin Balantekin Fuller 2002;

Sterile Neutrino WDM Models

Sterile neutrinos may be produced in early universe through off-resonance neutrino oscillations

Dodelson, Widrow; Abazajian, Fuller, Patel; Dolgov, Hansen; Asaka, Laine, Shaposhnikov ..

$$m_s = 3.27 \text{ keV} \left(\frac{\sin^2 2\theta}{10^{-8}}\right)^{-0.615} \left(\frac{\Omega_s}{0.24}\right)^{0.5}$$

Or oscillations on resonance with non-negligible lepton asymmetry

Fuller, Shi

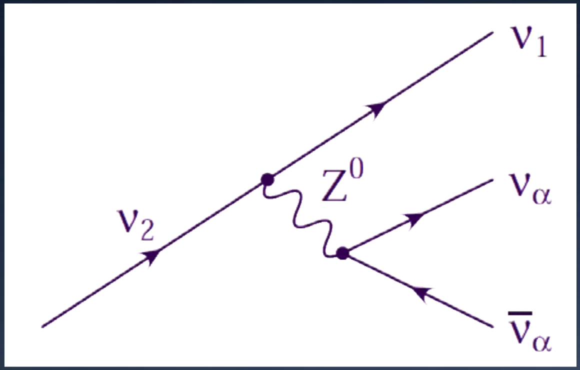
Or some other mechanism which do not involve oscillations, e.g.:

Inflaton decays Shaposhnikov, Tkachev

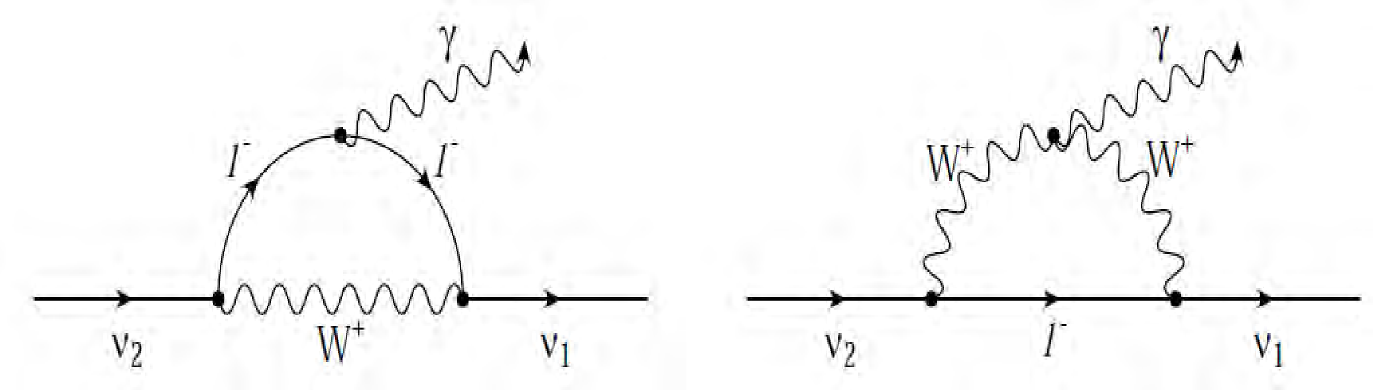
Higgs physics Kusenko

They are Also Testable Candidates

- Due to mixing, heavy neutrino is coupled to Z-boson, which allows 3ν decay mode



- The radiative decay mode is much suppressed but provides a detectable signal



$$\frac{1}{\tau} = (6.8 \times 10^{-33}\ \mathrm{s}^{-1}) \left[\frac{\sin^2 2\theta}{10^{-10}}\right] \left[\frac{m_s}{\mathrm{keV}}\right]^5$$

Pal, Wolfenstein 1982; Barger, Phillips, Sarkar 1995

Decay Signal

The corresponding line flux at $E=m_s/2$ from a DM reservoir of mass M at a distance D is:

$$\Phi_{\rm x,s} \simeq 5.1\times 10^{-18} \mathrm{erg\ cm^{-2} s^{-1}} \left(\frac{\rm D}{\rm Mpc}\right)^{-2} \left(\frac{M_{\rm DM}}{10^{11} M_{\odot}}\right) \left(\frac{\sin^2 2\theta}{10^{-10}}\right) \left(\frac{m_s}{\rm keV}\right)^5$$

Ideal object to study has to be:

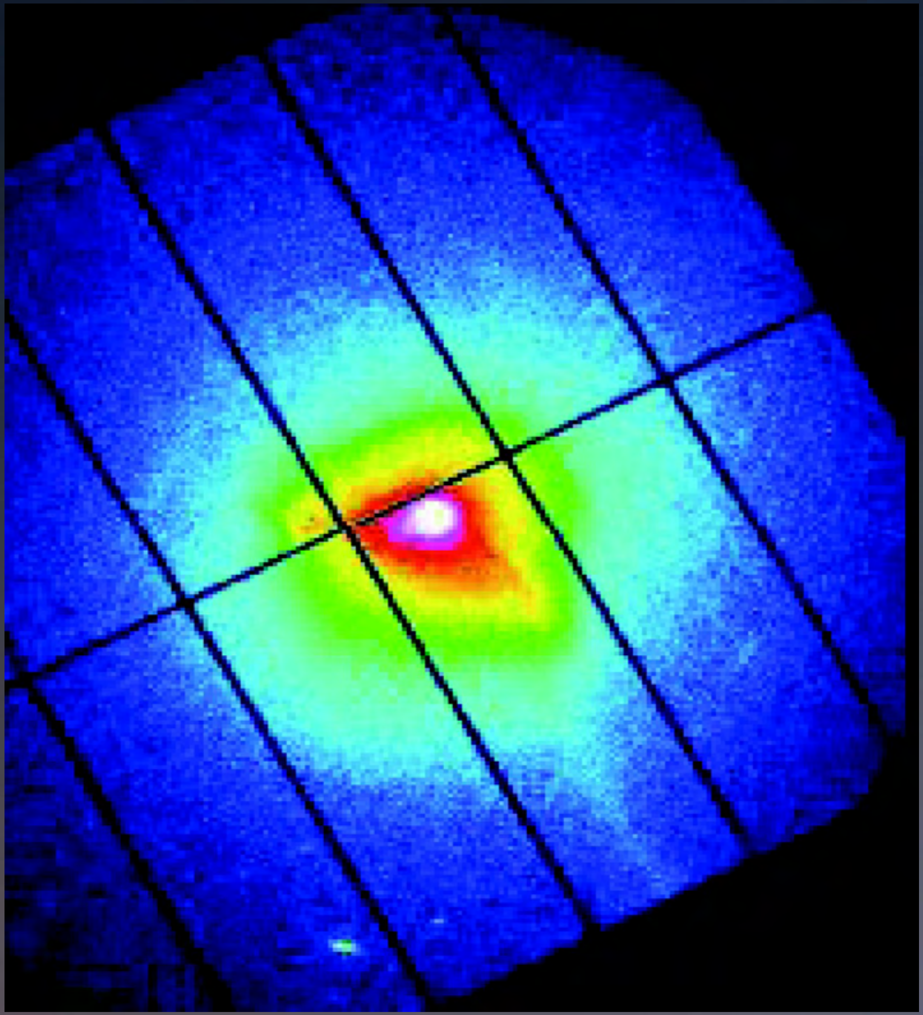
- nearby: small D
- massive and containing large amount of DM: large M
- devoid of large astrophysical backgrounds

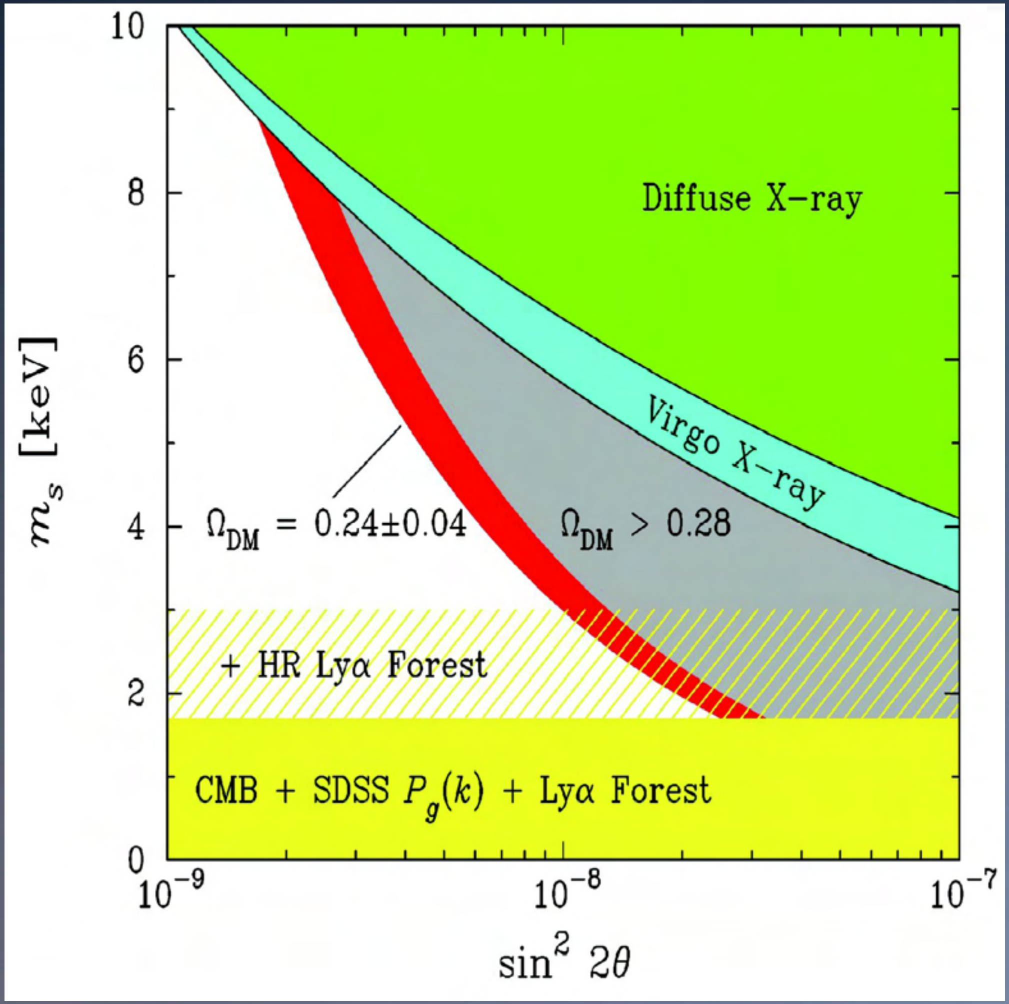
Considered Objects: Galaxy Clusters, Nearby Galaxies, Milky Way, Dwarfs in MW, Cosmic Backgrounds

Nearby Clusters

- Huge amount of DM and nearby but large astrophysical backgrounds

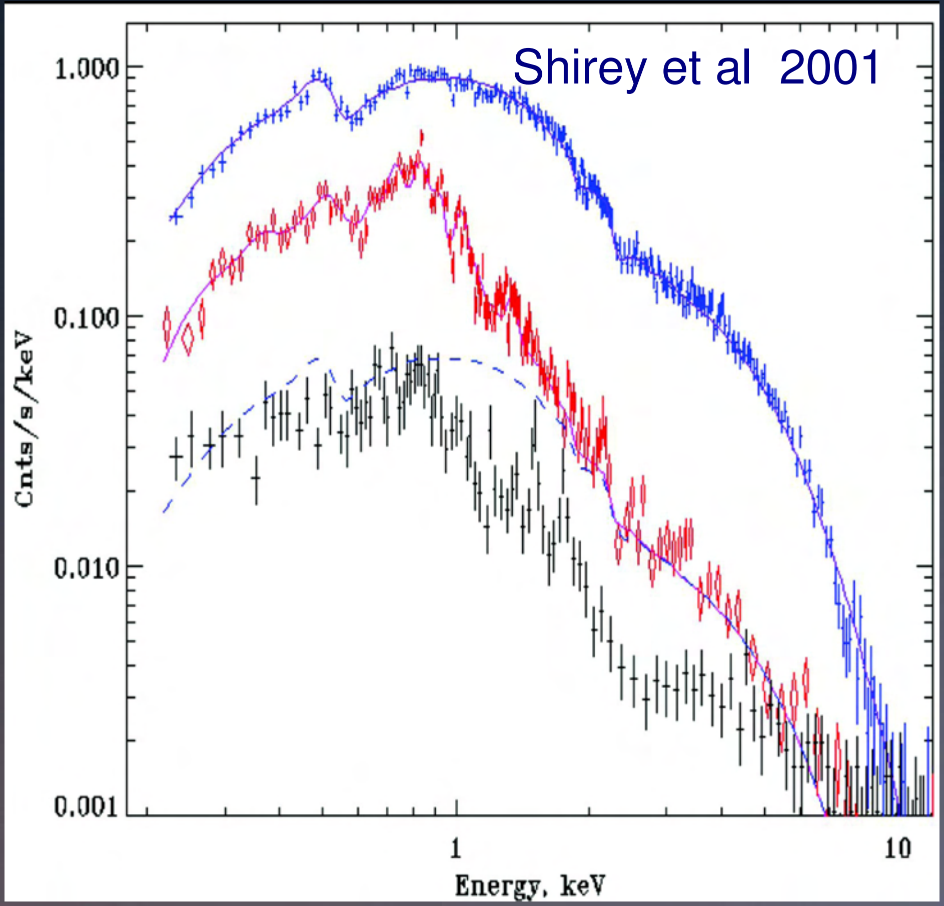
Abazajian Fuller Tucker 2001; Abazajian 2006

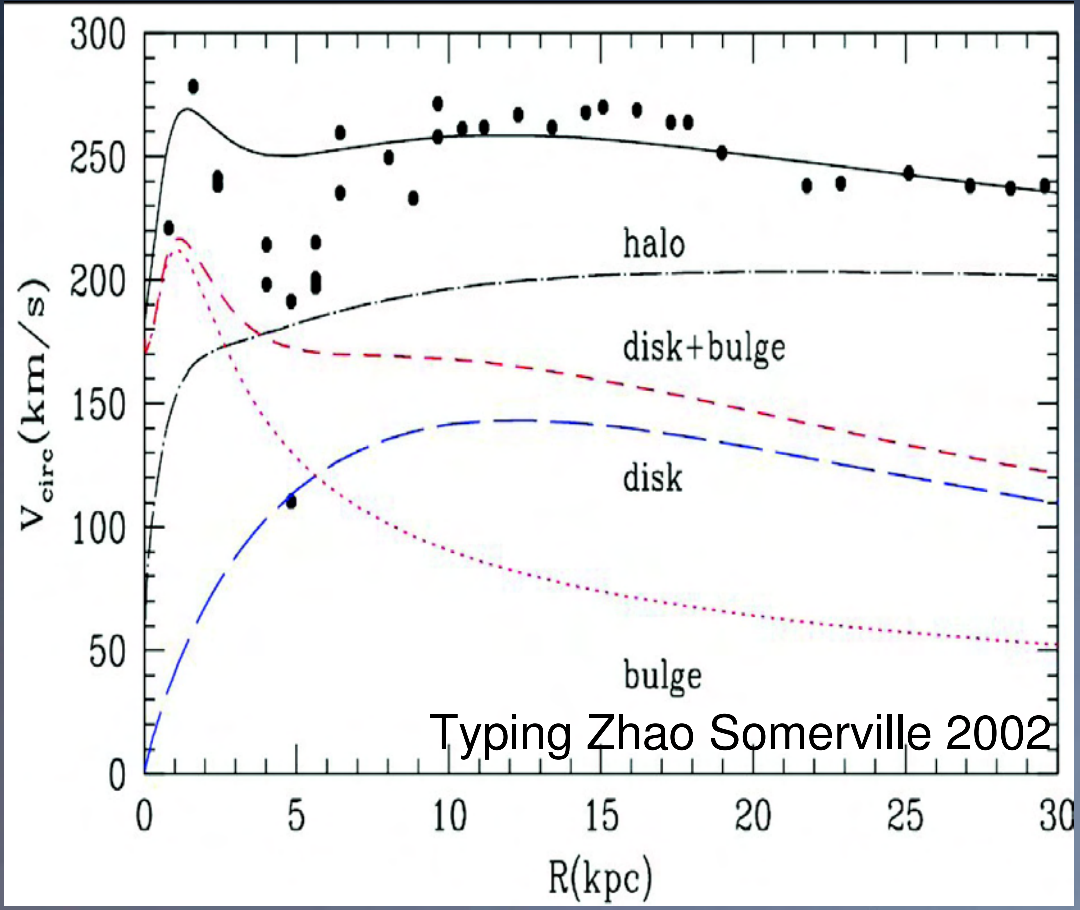




Andromeda (M31)

- Low astrophysical backgrounds: intrinsically low hot gas emission & bright point sources removed
- Well understood dark matter distribution based on extensive rotation curve data





Andromeda vs. Virgo

Galaxy Name	Andromeda (M31)	Virgo A (M87)
Distance (Mpc)	0.78 ± 0.02	15.8 ± 0.8
$\theta_{\rm fov}$ (arcminutes)	$5.0'$	$8.5'$
$M_{\rm DM}^{\rm fov}/10^{11} M_\odot$	0.13 ± 0.02	75 ± 8
$t_{\rm exp}$ (ks)	34.8	25.9
m_s (keV) (95% C.L.)	**3.5**	**8.2**

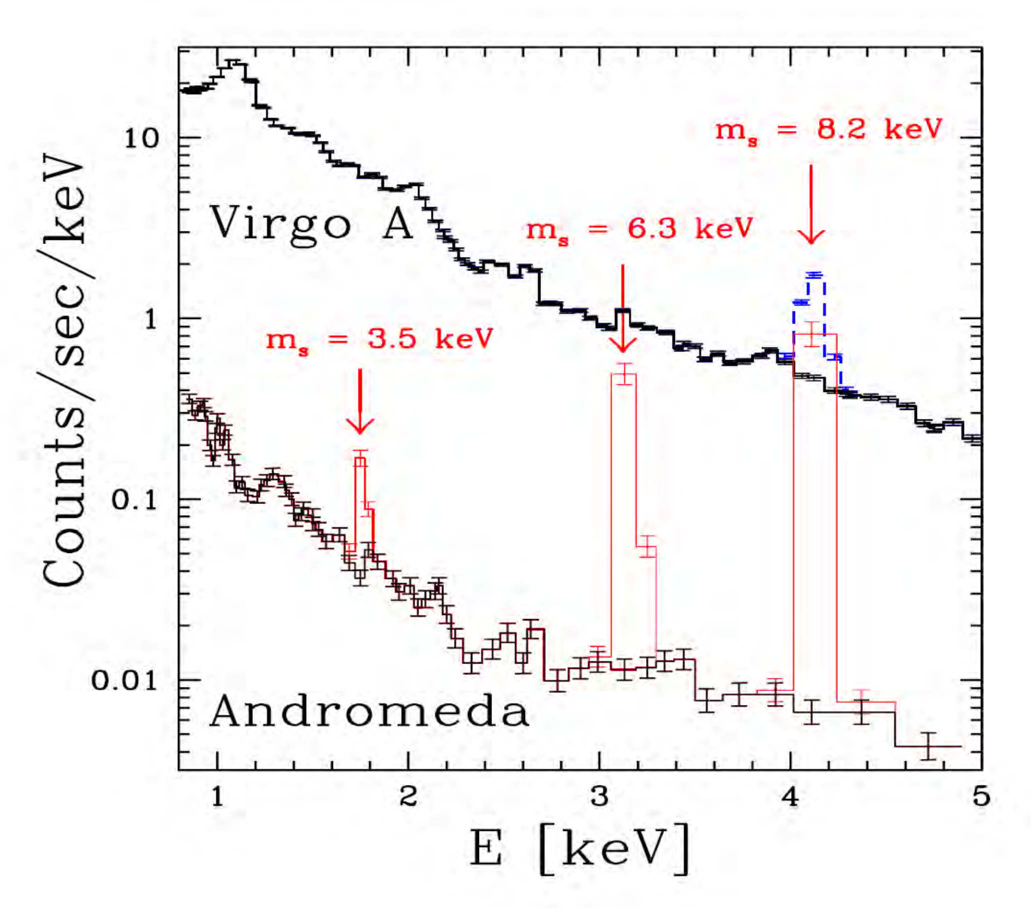
- Still Andromeda has decay signal comparable to more massive clusters

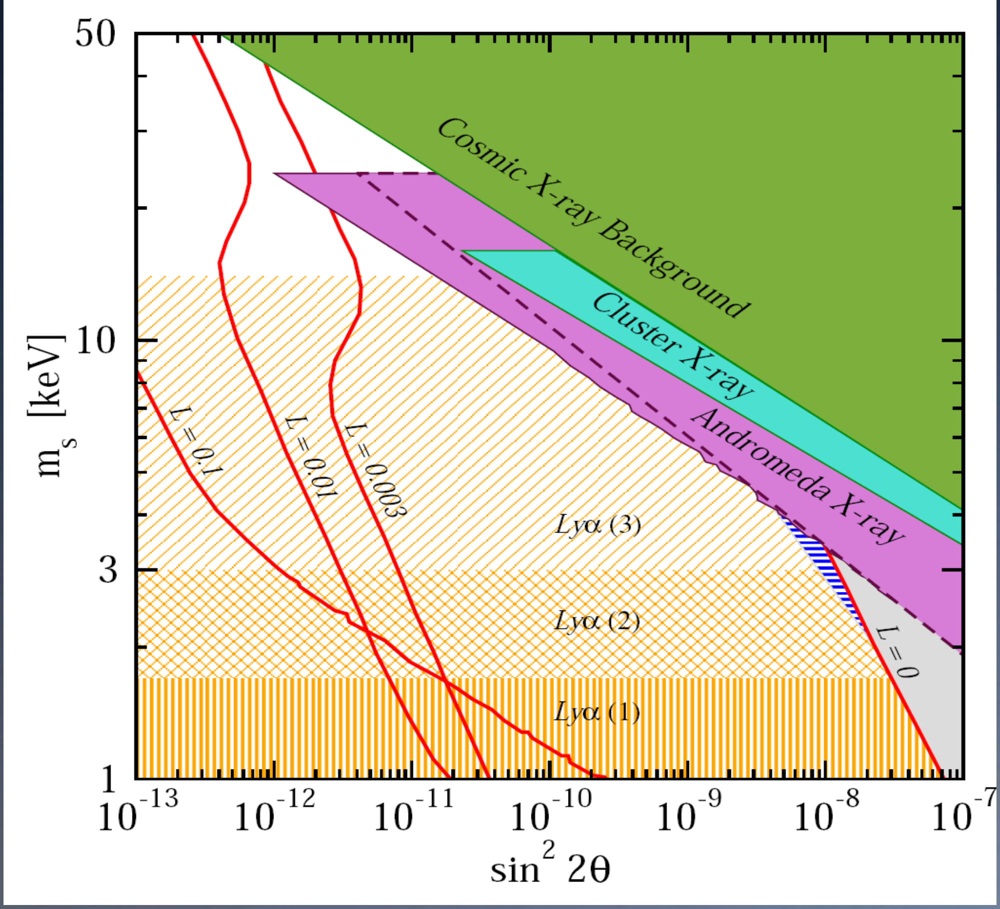
$$\frac{\Phi_{\rm x,s}^{\rm M31}}{\Phi_{\rm x,s}^{\rm M87}} = \frac{D_{\rm M87}^2}{D_{\rm M31}^2} \frac{M_{\rm DM,M31}^{\rm fov}}{M_{\rm DM,M87}^{\rm fov}} \simeq 0.71.$$

- Yet astrophysical backgrounds are many orders of magnitude lower, yielding much more stringent limits on sterile neutrino mass

Sterile Neutrino Mass and Mixing Plane

arXiv:astro-ph/0605424 C.Watson J. Beacom, H. Yüksel, T. Walker

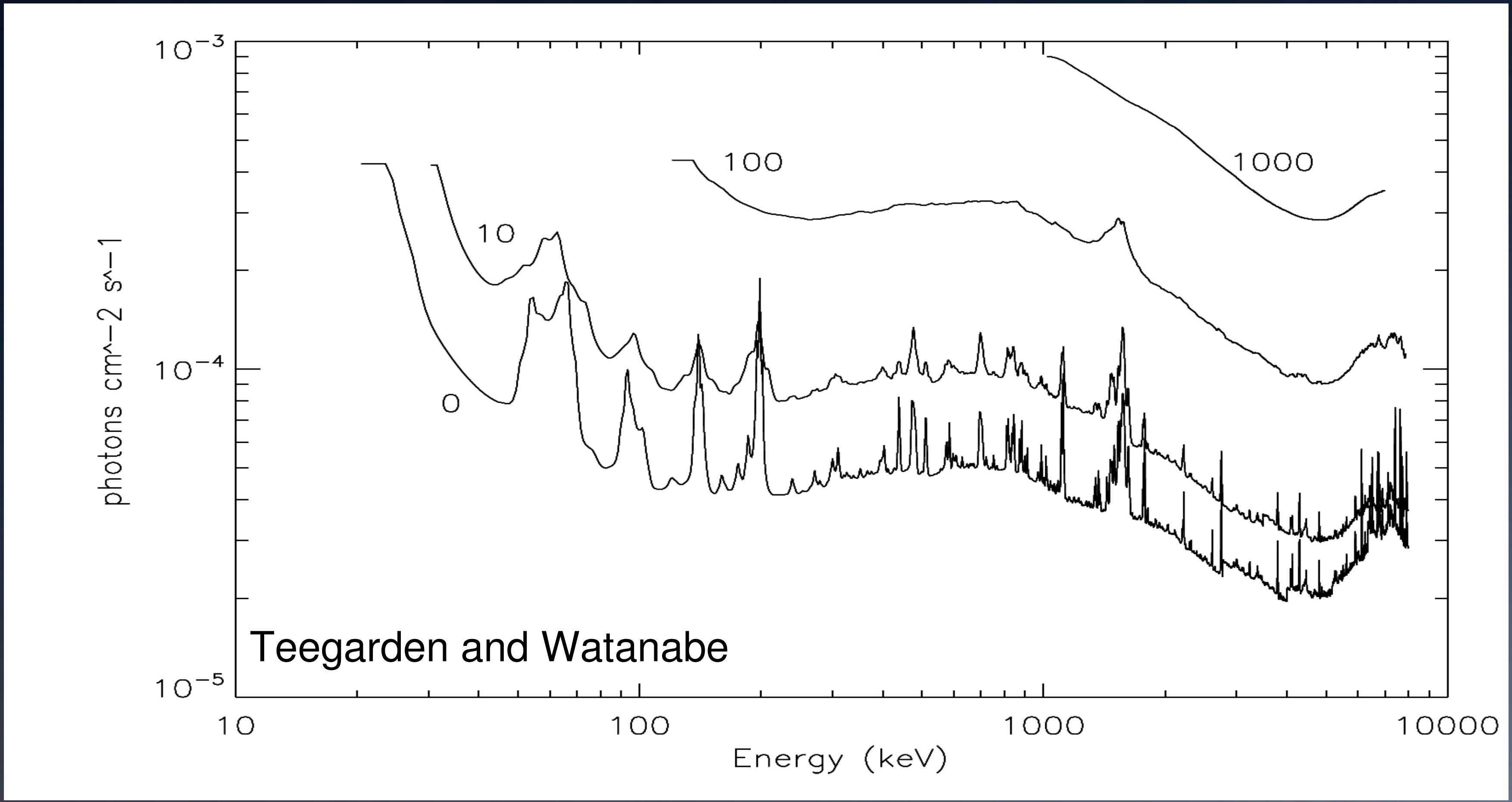




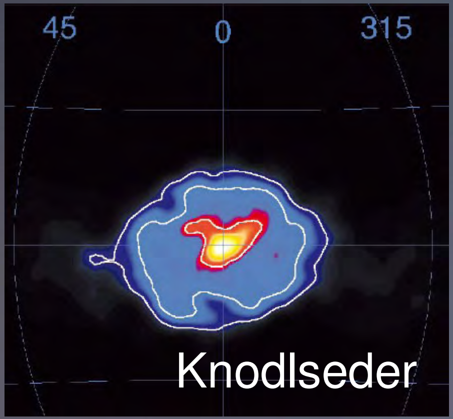
Viel et al; Seljak et al

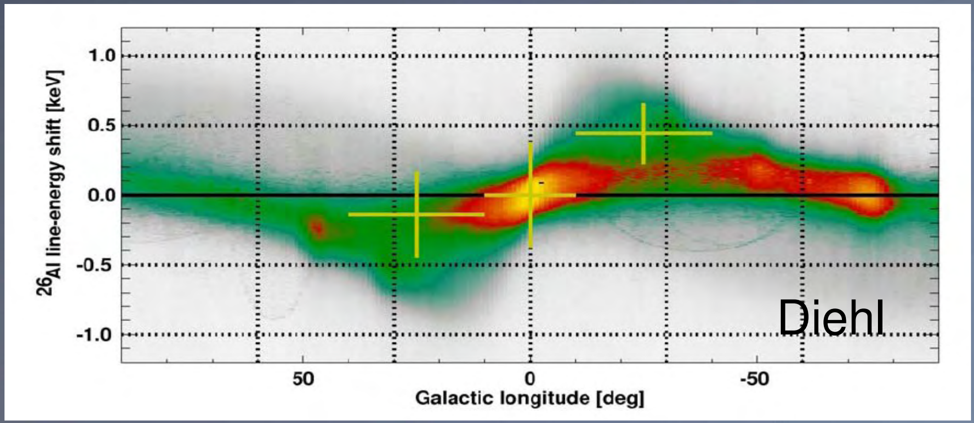
See also e.g: S.~Riemer-Sorensen, K.~Pedersen, S.~H.~Hansen and H.~Dahle
A.~Boyarsky, J.~Nevalainen and O.~Ruchayskiy,
K.~N.~Abazajian, M.~Markevitch, S.~M.~Koushiappas and R.~C.~Hickox

INTEGRAL γ-ray Line Search



Known lines recovered successfully:

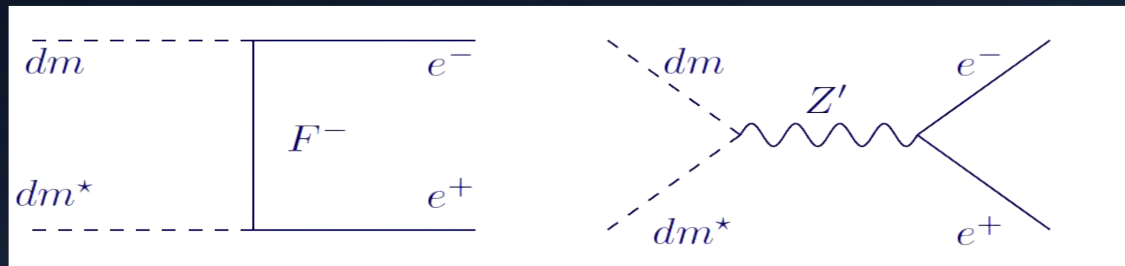




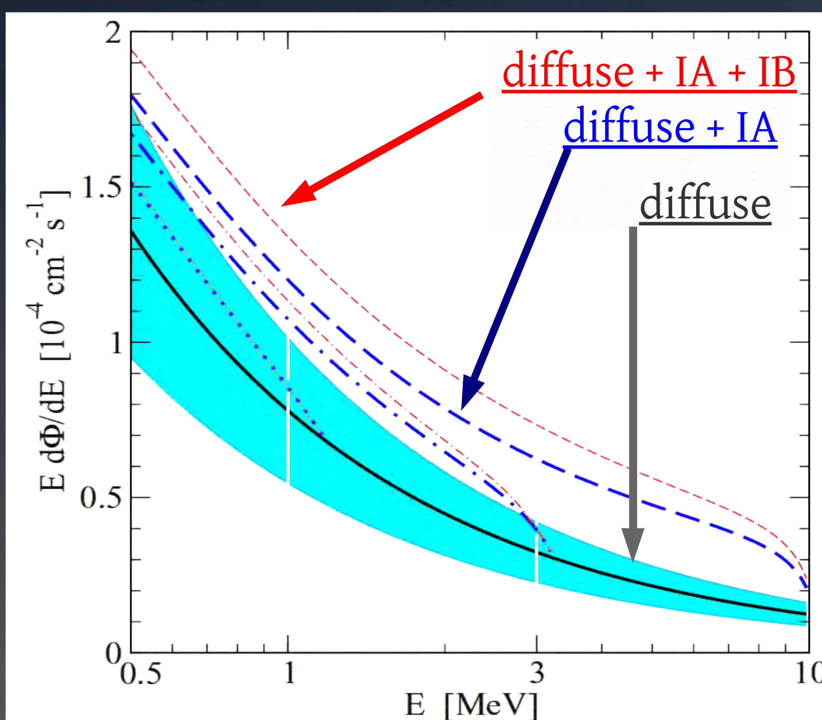
Digression: Positrons at the GC

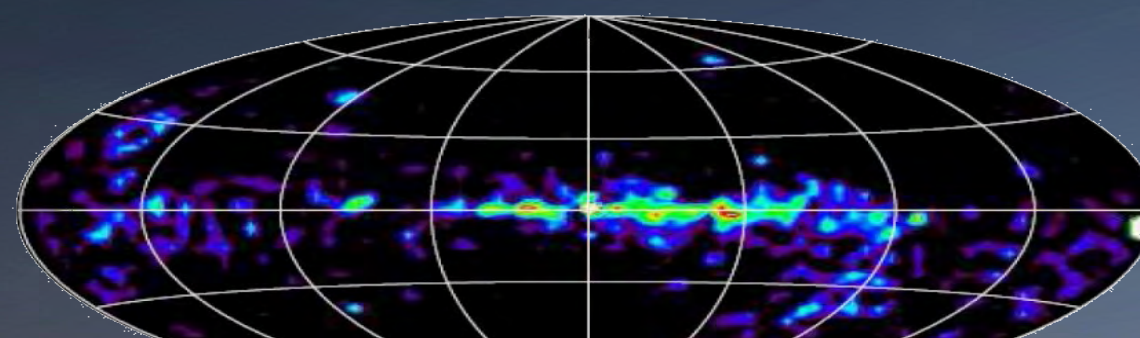
Light DM (proposed 1-100MeV) annihilates into e-e+ pairs

boehm, hooper, silk, casse, paul

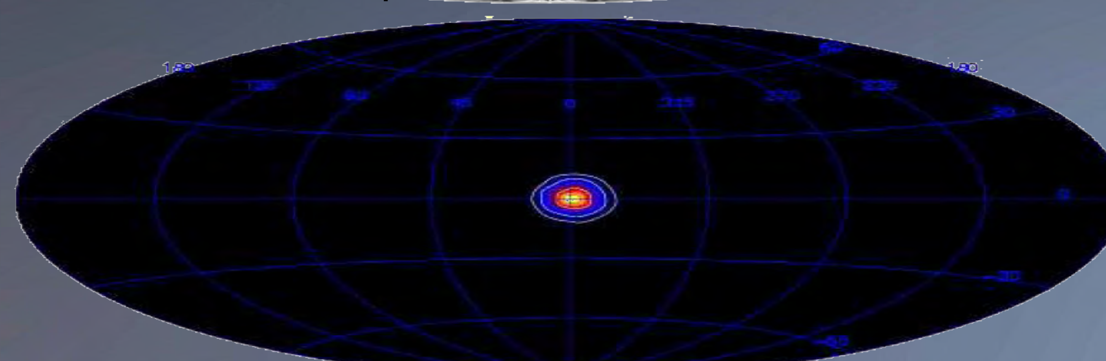


cannot be heavier than 3MeV due to Inflight Annihilation constraint





Comptel Diffuse 3-10 MeV



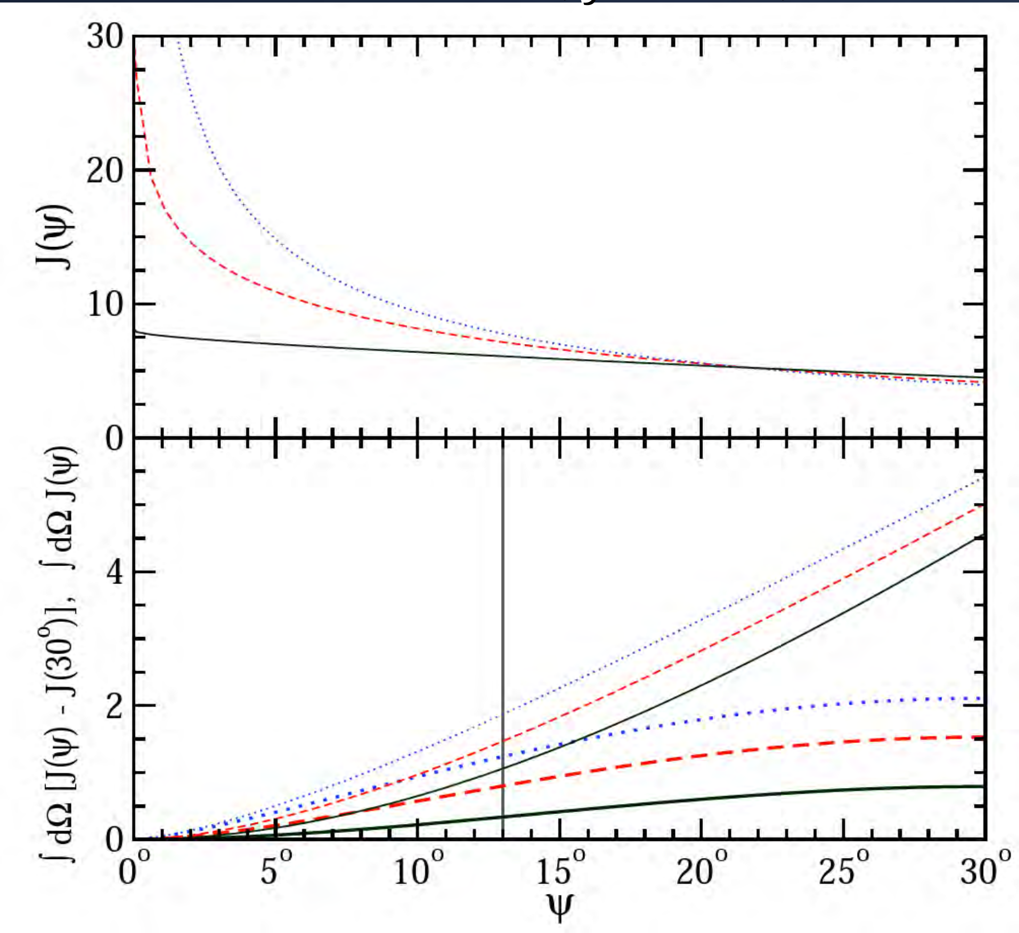
arXiv:astro-ph/0512411 J. Beacom, <u>H. Yüksel</u>

Milky Way Signal Needs Some Care

$$\mathcal{J}(\psi) = \frac{1}{\rho_{sc} R_{sc}} \int_0^{\ell_{max}} d\ell\ \rho\left(\sqrt{R_{sc}^2 - 2\,\ell\, R_{sc} \cos\psi + \ell^2}\right)$$

H. Yüksel, J. Beacom, C. Watson

$$\mathcal{I}(\psi) = \frac{\rho_{sc} R_{sc}}{4\pi m_s \tau} \mathcal{J}(\psi)$$



$$\mathcal{F}_s = \int_{\Delta\Omega} d\Omega\, \mathcal{I}(\psi) = \frac{\rho_{sc} R_{sc}}{4\pi m_s \tau} \int_{\Delta\Omega} d\Omega\ \mathcal{J}(\psi)$$

$$\Delta\mathcal{F}_s = \frac{\rho_{sc} R_{sc}}{4\pi m_s \tau} \int_{\Delta\Omega} d\Omega\ [\mathcal{J}(\psi) - \mathcal{J}(30^\circ)]$$

$$\frac{\rho_{sc} R_{sc}}{4\pi m_s \tau} = (4.3 \times 10^{-6}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}) \left[\frac{\sin^2 2\theta}{10^{-10}}\right] \left[\frac{m_s}{\mathrm{keV}}\right]^4$$

New Constraint on Sterile Neutrino WDM

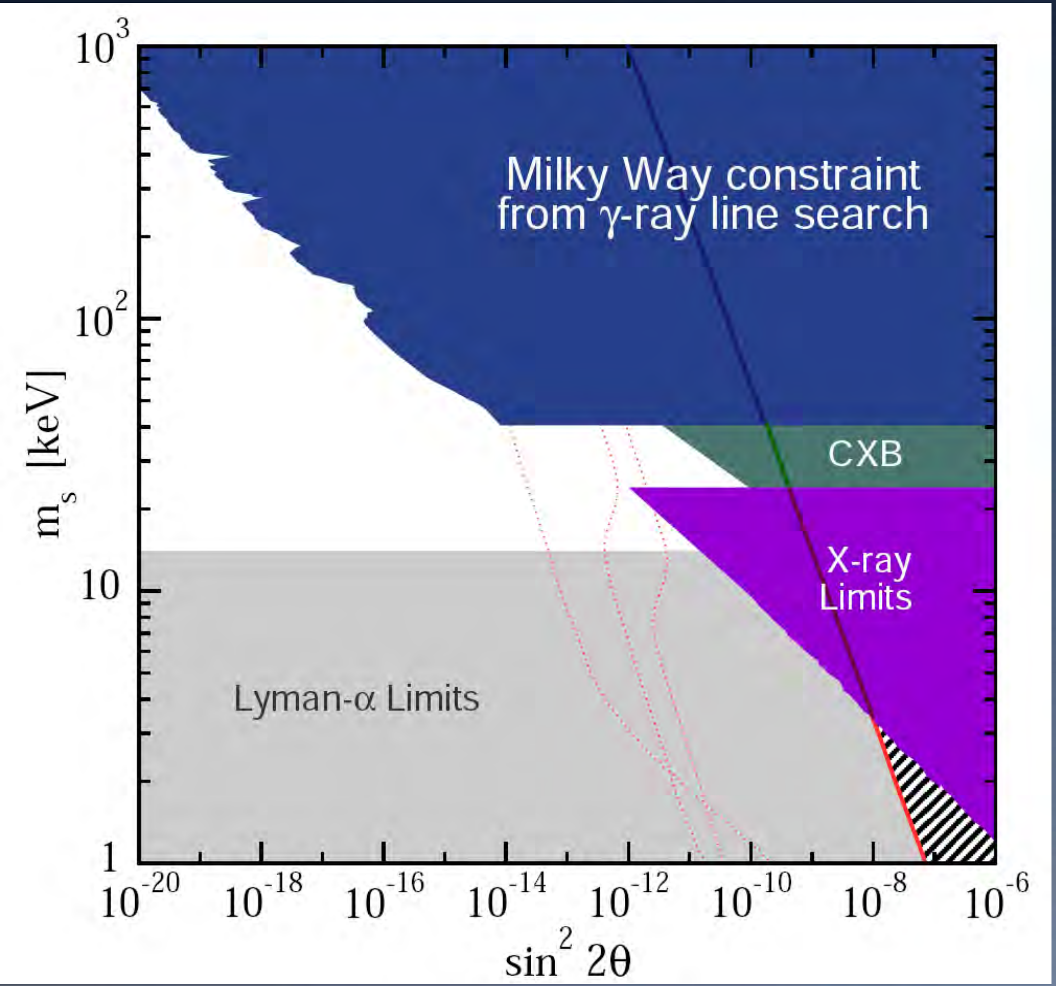
H. Yüksel, J. Beacom, C.Watson

$$\mathcal{F}_{lim} > \Delta\mathcal{F}_s$$

$$\mathcal{F}_{lim}(E) \simeq 10^{-4}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

$$\mathcal{F}_{lim}(E) > \frac{\rho_{sc} R_{sc}}{4\pi m_s \tau} \int_{\Delta\Omega} d\Omega \left[\mathcal{J}(\psi) - \mathcal{J}(30^\circ)\right]$$

$$m_s \lesssim \max\left[40\ \mathrm{keV},\ 0.85\ \mathrm{keV}\left(\frac{10^{-8}}{\sin^2 2\theta}\right)^{1/4}\right]$$



Especially important in constraining models in which sterile neutrinos have much smaller mixing

e.g. by Fuller, Shi

Summary (I)

Sterile neutrinos require only a minimal extension of Standard Model yet they provide so much!

They are an attractive DM candidate, resolving some issues with small scale structure

Their radiative decays allow possibility of direct discovery/exclusion, It is necessary to probe the full parameter space as defined by their mass and mixing

(II) MODEL INDEPENDENT CONSTRAINTS ON DARK MATTER ANNIHILATION TOTAL CROSS SECTION

Dark Matter Annihilations

WIMPSs can produce correct relic abundance Ω_M=0.3, and they can be

- produced in colliders
- discovered in direct detection experiments
- indirectly detected through Annihilation Products

- The annihilation cross section for such a thermal relic $<\sigma_A v> = 3\times10^{-26}$ $cm^3 s^{-1}$
- What if dark matter exists or gets mass only in the late universe?

General Upper Bounds

- Very large cross section can significantly modify halo (flatten cusps, produce cores):

$$\langle \sigma_A v \rangle_{\mathrm{KKT}} \simeq 3 \times 10^{-19} \frac{\mathrm{cm}^3}{\mathrm{s}} \left[\frac{m_\chi}{\mathrm{GeV}} \right]$$

Kaplinghat, Knox, and Turner

- The unitarity bound:

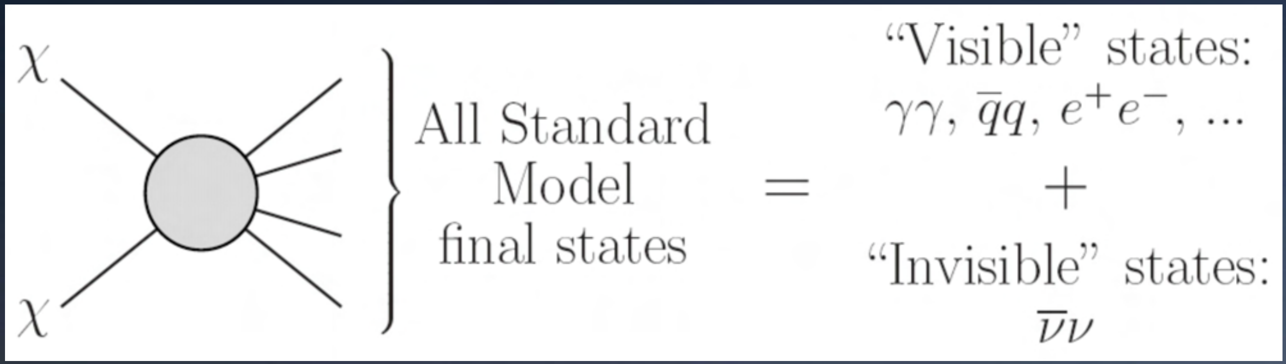
$$\langle \sigma_A v \rangle \leq 1.5 \times 10^{-13} \frac{\mathrm{cm}^3}{\mathrm{s}} \left[\frac{\mathrm{GeV}}{m_\chi} \right]^2 \left[\frac{300\ \mathrm{km/s}}{v_{rms}} \right]$$

Hui

- Are there any other general bounds?

Avoid Model Dependencies

- Assume DM annihilations only produce Standard Model final states (e.g. purely sterile neutrinos are not considered)



Beacom Bell Mack

- Stringent upper limit on total annihilation cross section can be obtained by assuming only neutrinos are produced in final states (worst case)
- Anything else will eventually produce much more visible gamma rays (leading to a stronger limit)

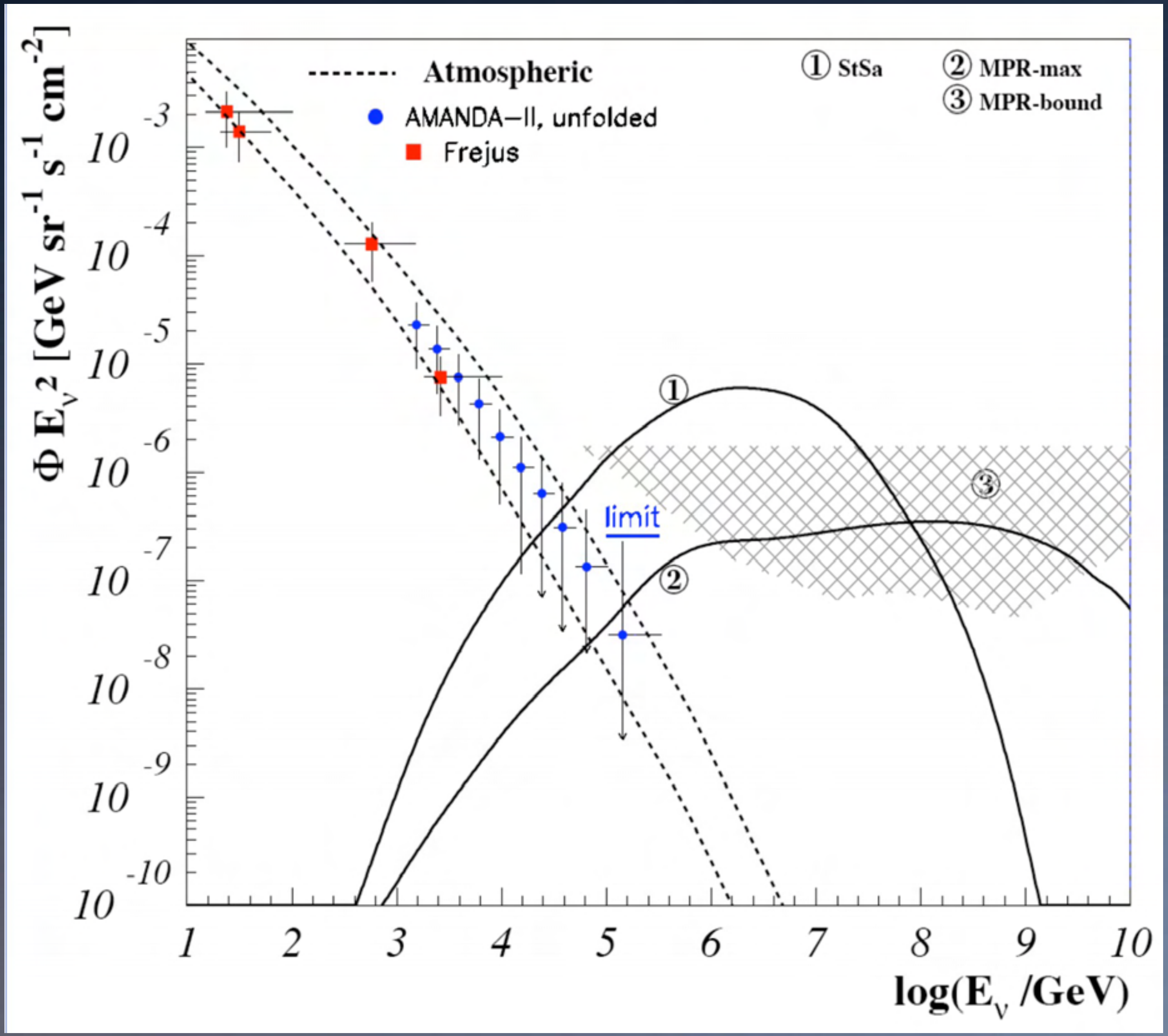
Atmospheric Neutrino Flux

Based on regularized unfolding which may miss a peaked signal

Frejus (Low E)

Amanda (High E)

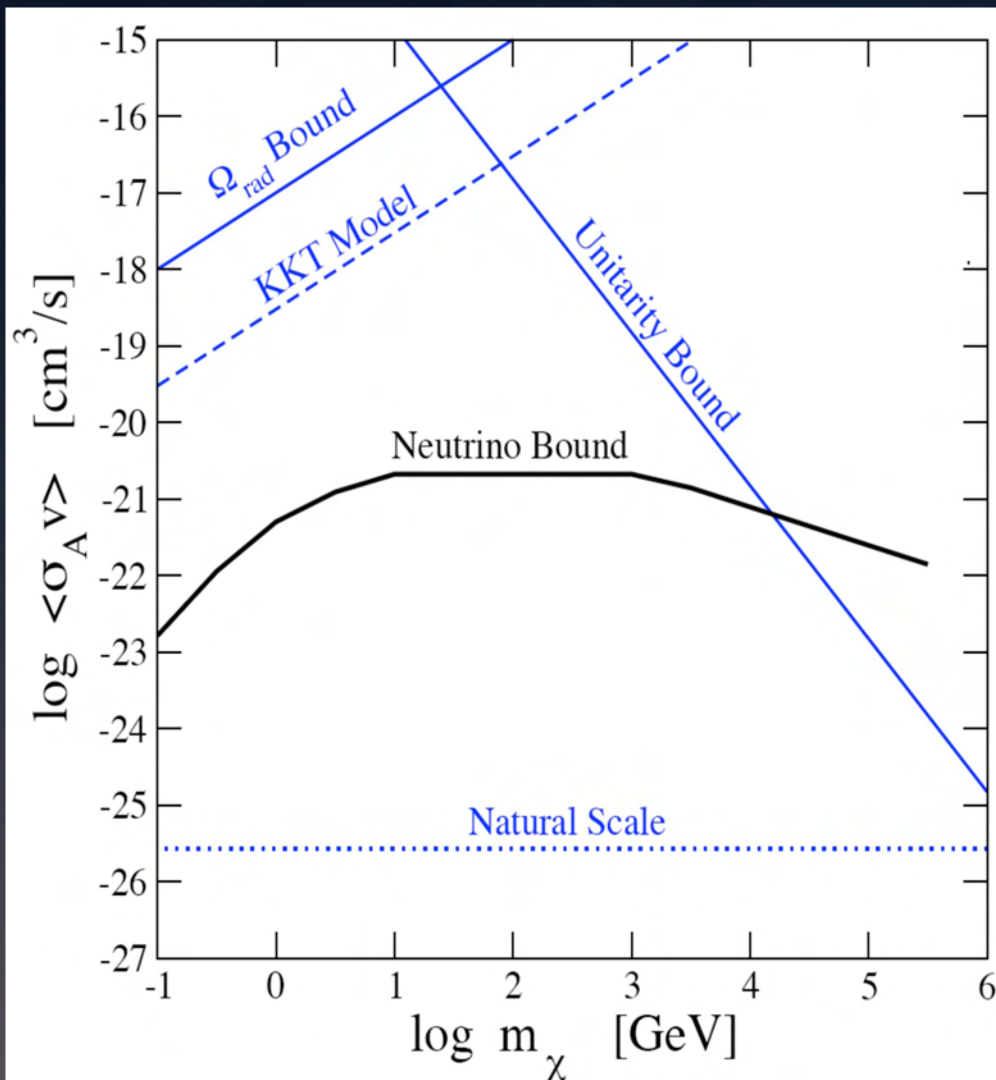
also SK data



astro-ph/0509330

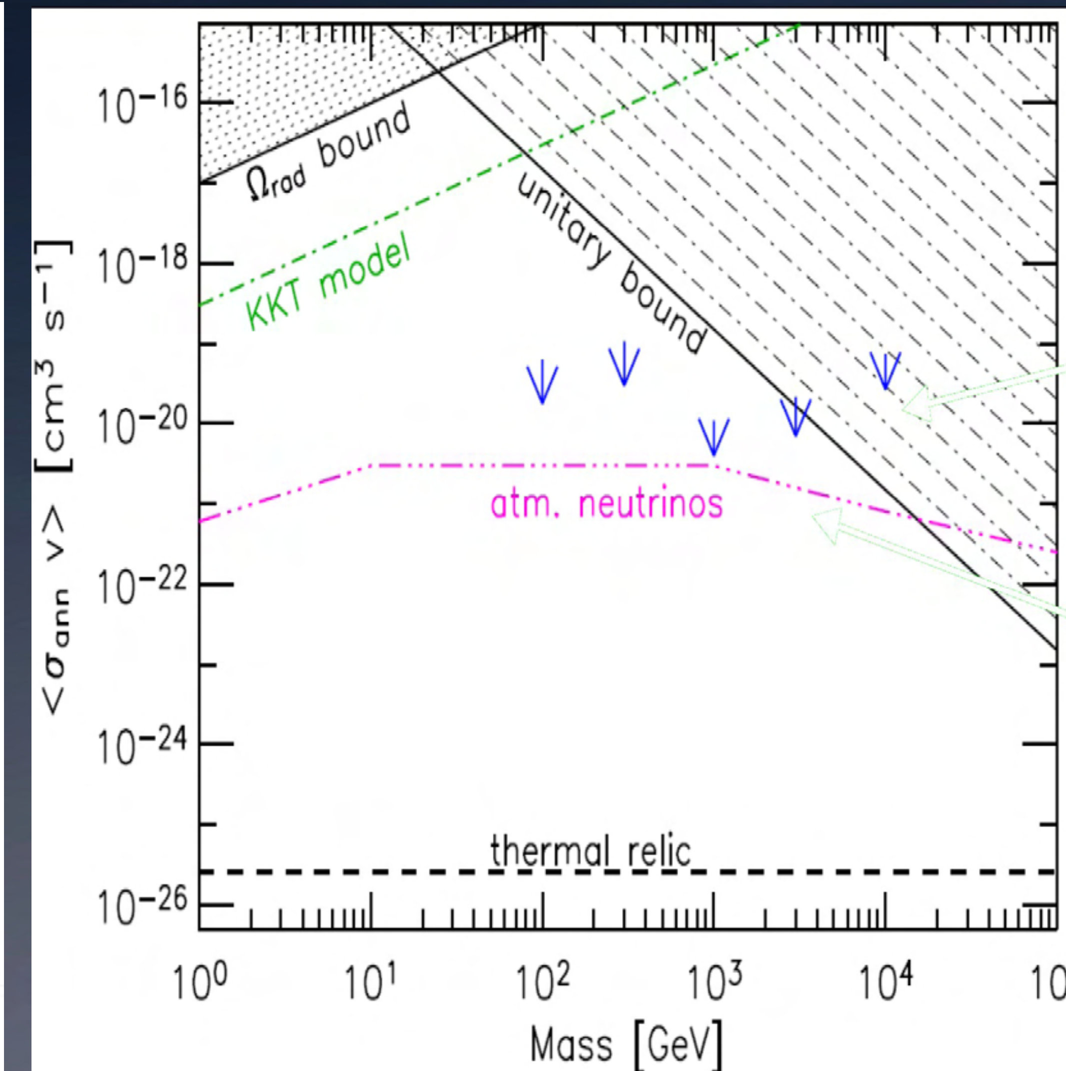
Bounds from Cosmic Signal & Cascades

$\chi\chi \rightarrow \upsilon\upsilon$ Cosmic Signal



Beacom Bell Mack

$\chi\chi \rightarrow Z\upsilon\upsilon$ Electroweak Cascades



Kachelriess Serpico

Annihilations in the Halo

Depends on the line of sight integration (traces DM density squared):

$$\mathcal{J}(\psi) = \frac{1}{R_{sc}\rho_{sc}^2} \int_0^{\ell_{max}} \rho^2(\sqrt{R_{sc}^2 - 2\,l\,R_{sc}\cos\psi + l^2})\,d\ell$$

$$\ell_{max} = \sqrt{(R_{MW}^2 - \sin^2\psi R_{sc}^2)} + R_{sc}\cos\psi$$

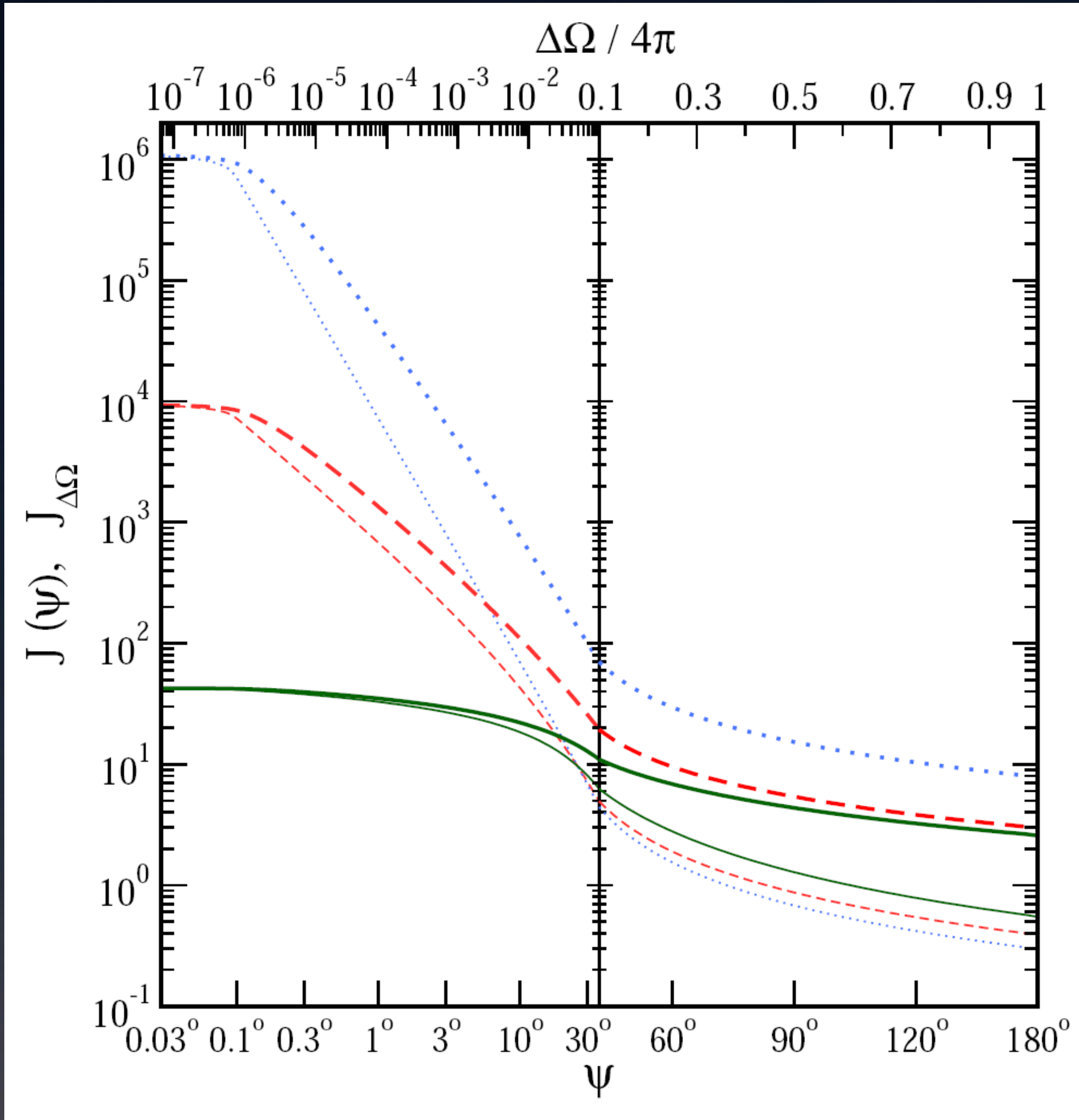
Average of los within a cone around the GC

$$\mathcal{J}_{\Delta\Omega} = \frac{1}{\Delta\Omega} \int_0^{\cos\psi} \mathcal{J}(\psi')\,2\pi\,d(\cos\psi')$$

$$\Delta\Omega = 2\pi(1 - \cos\psi)$$

The average intensity of the annihilation products

$$\frac{d\Phi_{\Delta\Omega}}{dE} = \frac{\langle\sigma_A v\rangle}{2} \mathcal{J}_{\Delta\Omega} \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN}{dE}$$



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	J_{Ang}	J_{ave}	J_{iso}	f_0
Moore	102	8	0.3	5
NFW	26	3	0.4	0.5
Kravtsov	24	5	1	0.2
Canonical	**25**	**5**	**0.5**	**1**

Cosmic vs. Halo Signals

Cosmic signal can be cast into (see e.g. Ullio et al)

$$\frac{d\Phi}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{\Omega_\chi^2 \rho_c^2}{4\pi m_\chi^2} \frac{c}{H_0} \int \frac{dN(E')}{dE'} \frac{(1+z)^3 f(z)}{h(z)} dz$$

f describes clustering relative to smooth halo

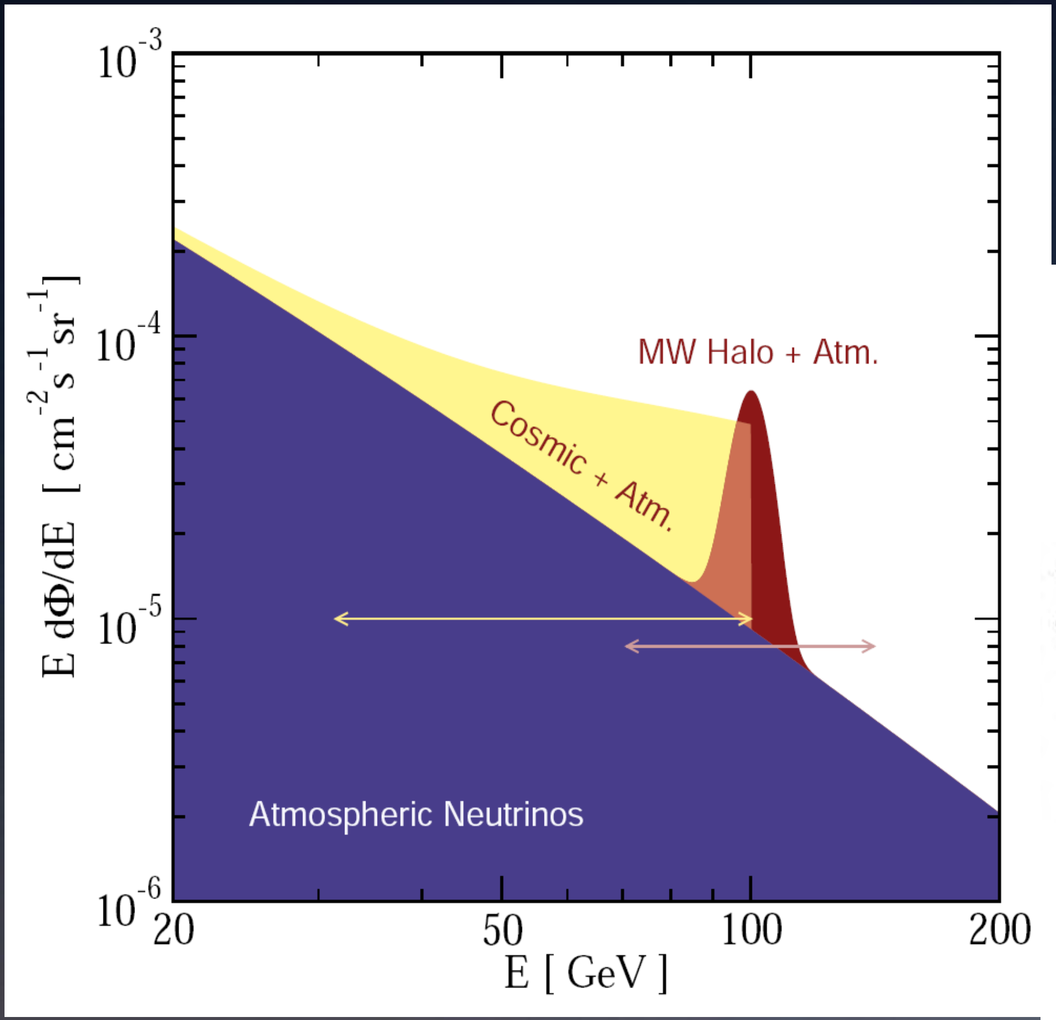
$$f(z) = f_0 \times 10^{0.9(\exp[-0.9z]-1)-0.16z} \qquad h(z) = [(1+z)^3 \Omega_\chi + \Omega_\Lambda]^{1/2}$$

The ratio of the Halo signal to Cosmic signal tell us which one dominates:

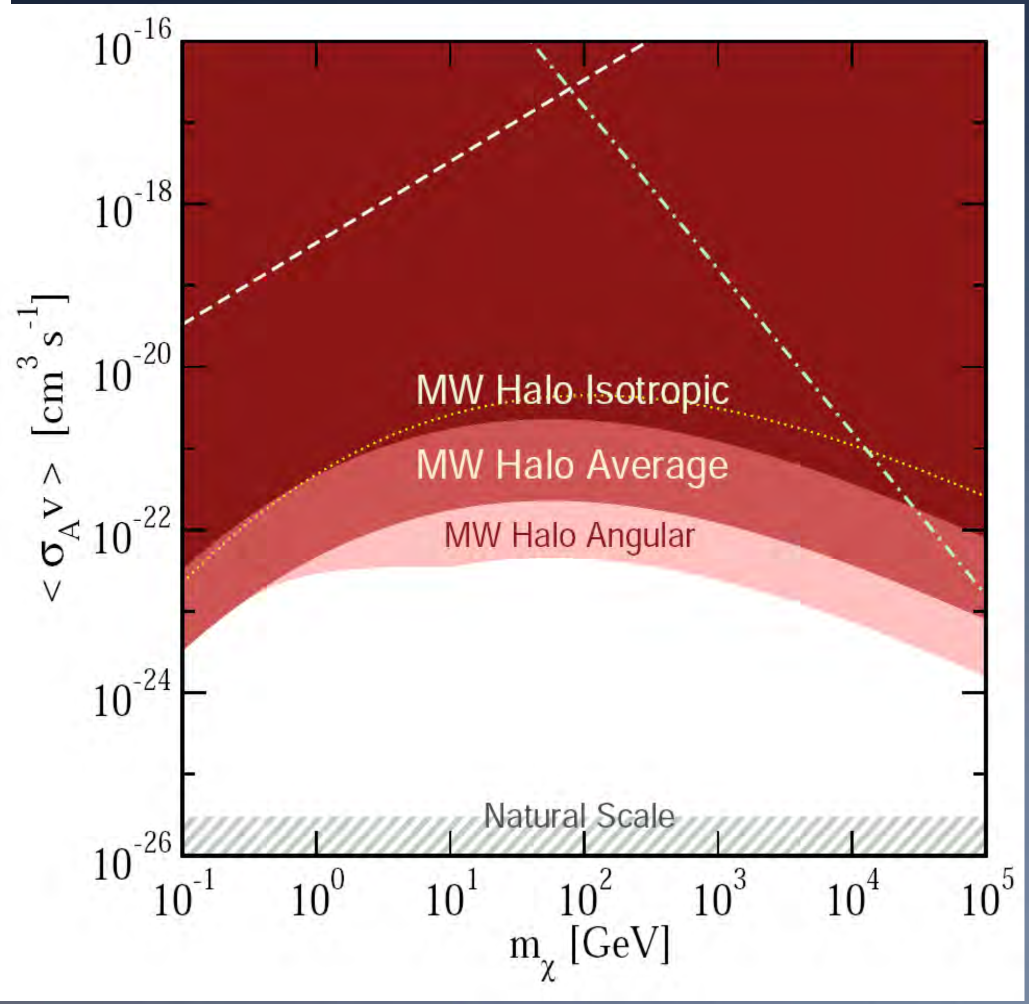
$$\frac{\Phi^H_{\Delta\Omega}}{\Phi^C} \sim \frac{\mathcal{J}_{\Delta\Omega} R_{sc} \rho_{sc}^2}{c H_0^{-1} \Omega_\chi^2 \rho_c^2 f_0} \sim 10^5 \frac{\mathcal{J}_{\Delta\Omega}}{f_0}$$

For NFW, $f_0 = 0.5 \times 10^5$, the Halo Isotropic will dominate over truly Cosmic signal for flatter profiles

Bound on $\langle\sigma_A v\rangle$ from Milky Way Halo



$\chi\chi \rightarrow \upsilon\upsilon$



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Cosmic vs. Halo

While both suffer from uncertainties such as the concentration parameter and the shape of the halo, the halo signal on large scales is overall better known, and less uncertain than cosmic signal

The isotropic component of the halo signal is especially important for flatter profiles, for which it dominates over any truly cosmic signal. For cuspy profiles, the Halo Angular would be even more constraining than displayed in our

The cosmic signal is broadened in energy by redshifting, making it harder to identify over the smoothly varying atmospheric neutrino spectrum

Gamma rays from cosmic DM annihilations are attenuated at high energies, thus the statement that anything other than neutrinos will be more detectable may not be always fully applicable for the cosmic signal (the halo signal will still be present)

SUMMARY (II)

A new improved upper bound on the dark matter annihilation cross section in the late universe, improving the unitarity bound and bound from cosmic DM annihilations

Especially interesting at energies > 100 GeV, in which there are no gamma-ray data on large scales

Dedicated analyses should improve by 10-100

- First, take advantage of the sharp feature
- Second, use more realistic data uncertainties
- Third, use signal and background flavor ratios
- Fourth, use high-energy muon spectra

Which Dark Matter Candidate?

Conclusions

What is the nature of DM? We focus on two scenarios in which Neutrinos:

- either can be the DM (as sterile neutrinos)
- or can provide constrains on the DM total self annihilation cross section (as active neutrinos, being the least detectable in the Standard Model) in a model independent way

New Physics Beyond the Standard Model?

Upcoming super-sized detectors with unprecedented statistics and precision, like:

- GLAST, IceCube, LHC, Hyper-K, etc....
- or X-Ray/γ-Ray Satellite Missions like GLAST, const-X

may provide crucial clues in solving this mystery